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**MICROMECHANICAL INVESTIGATION OF FATIGUE DAMAGE IN UNI-DIRECTIONAL FIBRE COMPOSITES**

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## ABSTRACT

In this study, 3D x-ray computed tomography (XCT) is used to study fatigue damage mechanisms of a uni-directional (UD) glass fibre composite used in wind turbine blades. The challenges related to using 3D XCT for fatigue damage assessment over time is outlined, and a cut-out of a specimen previously subjected to tension-tension fatigue loading is examined. Broken UD load-carrying fibres are observed locally close to the thin off-axis backing support layers and are spreading out in a local damage zone in the UD bundle close to the backing. The common factors of the fatigue damaged regions found in this study were intertwining backing bundles in direct contact with the UD bundle and a locally high fibre volume fraction at the backing. Other factors like fibre misalignment and fibre radii could have an effect; however this is not obvious from the obtained results. Further studies on a larger dataset should be performed to examine this in more detail.

## INTRODUCTION

The worldwide demand for energy is increasing, and therefore the demand for new and cost competitive renewable energy sources has been increasing steadily the recent years. More specifically, the supply of wind energy solutions has more than doubled the past 5 years, and it is expected to keep increasing the following years [1]. The main driver in the wind energy sector is to reduce the cost of energy of a wind turbine in order to become competitive against fossil fuels. A way of achieving a lower cost of energy is by reducing the amount or cost of material, or increasing the power output of the turbine. So far, increasing the blade length has decreased the cost of energy for a turbine, as the power output increases proportionally to a power of 2 with the blade length (the swept area of the rotor). One of the main challenges in designing a wind turbine lies in the blade design, as the blades are subject to a variety of loads such as wind and gravity loads.

To reduce the gravitational loads (lower blade mass) and material costs, the blades are designed mainly using composite and sandwich materials since these materials offer the most suitable combination of stiffness, strength and fatigue resistance. By using composite and laminate materials the blade cross section is customized to match the loads present in the structure. The bending loads, caused by the wind and blade weight, are carried by spar caps made of uni-directional (UD) composite material. The shear loads are usually taken up by a sandwich web structures within the cross section, i.e. consider an I-beam in bending. [2,3]

Wind turbine blades are subject to a large number of stochastic fatigue load cycles during their life time as a consequence of the blade rotation and wind action. The blades are subjected to repeated edge-wise bending from the gravity loads, and repeated flap-wise bending from the wind loads. The fatigue damage mechanisms in UD composites are not well understood and this leads to the necessity of safety factors in the blade design.

As a consequence, fatigue is one of the main limiting factors for designing longer blades, and therefore of great interest to explore.

### *Previous studies and literature review*

During fatigue loading in fibre composites multiple failure modes occur; some of which are: fibre fracture, matrix cracking and delamination [8]. Several studies have considered fractures in off axis plies by delamination between fibre and matrix where they are trying to relate the material behaviour to the observed crack density [6,7,8]. Most of these studies disregard fibre breakage in the 0° layers.

In a previous study by Zangenberg et al. [4] the fatigue damage in a UD glass fibre composite made from a non-crimp fabric with backing was examined. Backing is a relatively thin supporting layer of close to transverse fibres to which the UD bundles are stitched in order to hold the fabric in place during fabrication and handling. In this study, it was found that the fatigue damage would progress by cracks propagating from the backing layers into the load-carrying UD layers. The backing layers crack first by debonding between fibres and matrix as a consequence of being close to transversely oriented relative to the loading direction. However, despite the backing layers being relatively thin, the cracks in the backing bundles were observed to propagate into the UD bundles causing the load carrying fibres to break. The main observations were that the cracks would tend to propagate into the UD layer to which they were stitched, and that a resin rich layer could cause the crack to stop propagating. The observations were carried out using the scanning electron microscope (SEM) and were backed up by burning off the matrix and examining the fibres in optical microscope.

The current study uses the 3D x-ray computed tomography (XCT) technique for fatigue damage assessment of a UD glass fibre composite similar to the composite used for wind turbine blades. This study is an initial step in a larger vision of being able to obtain a 3D image of damage progression during a tension-tension fatigue test. This is possible as 3D XCT is a non-destructive imaging technique, however it is necessary to push the equipment against its limits.

## DAMAGE ASSESSMENT USING 3D X-RAY COMPUTED TOMOGRAPHY

Techniques used by Zangenberg et al. [4] were all destructive techniques which set some limitations for analysing the damage evolution of the material. A technique like SEM imaging can obtain a good image resolution; however, as any regular microscope it provides 2D images. It is possible to get a 3D image of the material through repeated grinding and imaging, but this is a very slow process and ends up destroying the sample. The possibility of introducing additional damage to the material when cutting also exists. The burn-off technique is an advantageous and simple method for confirming the observations; however, it might be difficult to examine the specific differences in the local backing lay-up at positions with and without broken UD fibres, as the fibres might have moved compared to how they were positioned prior to burning. As the damage in the material truly is a 3D feature, a technique like 3D x-ray computed tomography is thus of interest.

### *The 3D X-ray Computed Tomography Technique*

The 3D XCT technique is a non-destructive imaging technique where the sample is placed between an x-ray source and a detector. The source sends x-rays towards the sample where some x-rays are absorbed and thereby only some x-rays penetrate through to the detector and creates a projection image. The sample is rotated 360 degrees with a given step size angle, and a projection image is stored for each rotation step.

Using a reconstruction algorithm, the projection images are transformed to a 3D reconstructed volume. The x-ray absorption of the material is related to the atomic density, and the difference in atomic density is what creates contrast in the image. Therefore x-ray imaging is useful for imaging glass fibre composites, as the difference in atomic density for the glass and the matrix material is around a factor of 2. In contrast, using 3D XCT on carbon fibre composites is more challenging as the atomic density of polymer and carbon is somewhat similar; however challenging it can be done with longer scan times.

The main challenge in using the 3D XCT technique for damage assessment is to obtain a sufficient image resolution in order to see the micro-structural damage. Performing 3D XCT on a full size fatigue test specimen is challenging for several reasons:

- The cross-section of a fatigue test specimen (usually width 25mm and thickness around 5mm) has a large width to thickness ratio which has a negative effect on the image quality as the x-rays has to penetrate a varying sample thickness throughout the rotation of the sample.
- The spatial resolution of the image decreases with increasing sample size as a consequence of increased noise in the image. Additionally, the exposure time has to be increased to get a sufficient number of x-rays reaching the detector, which leads to longer scan times.
- The image resolution decreases with increasing field of view (FOV) size as a consequence of a fixed amount of pixels on the detector.

Micro-structural material damage like broken fibres or matrix cracks are small features (a few microns compared to approximate fibre diameter around 17 microns) and since the considered volume has to be representable for the larger scale, the challenges stated above must be considered to find suitable scan settings. A way to overcome these challenges is to cut the sample smaller with the risk of an unrepresentative volume element, or to apply pre-tension to the sample while scanning to open up cracks. Multiple scans can be performed and stitched together to increase the field of view, however the scan times for scans with small FOV are usually long (15-50 hours).

In this study, 3D XCT was performed on a cut-out of a fatigue test specimen, but still serves to provide valuable information about the fatigue damage mechanisms of the UD glass fibre composite in tension-tension fatigue. Work is ongoing on applying pre-tension to the sample while scanning so that in the future the technique can become a truly non-destructive method for fatigue damage assessment of the entire test specimen.

## COMPOSITE LAY-UP AND STRUCTURE

The considered material is a non-crimp fabric consisting of layers of bundles of UD fibres held in place by backing fibre bundles to which the UD bundles are stitched. The backing bundles are present to keep the UD fibre bundles in place and give a fabric-like structure for fabrication. The considered material has the lay-up $[b/0,b/0]_s$ as illustrated in Figure 1.

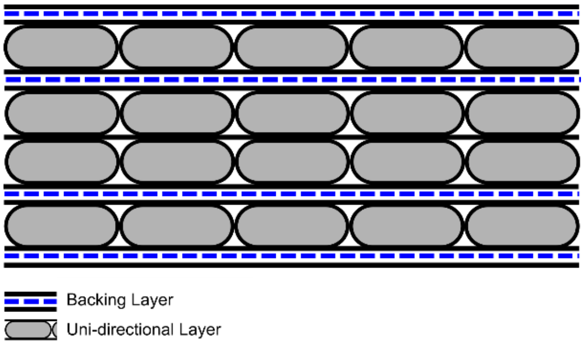


*Figure 1: Sketch of [b/0,b/0]$_S$ lay-up where the dashed lines show the backing layers. The sketched layer thickness is not in scale, however the backing layers are thinner than the UD layers.*

The backing layers do not contribute particularly to the axial strength of the material; however, it does provide some degree of transverse and shear stiffness to the material. For this reason, and because it is necessary for fabrication and handling, it cannot simply be excluded in the lay-up. For the test samples used in this study, the load carrying UD fibres are made of a high modulus glass (HM-glass), the backing fibres are E-glass, and the matrix material is a thermoset polyester material. The composite was fabricated using vacuum assisted resin transfer moulding (VARTM) injection.

## SPECIMEN GEOMETRY AND LOADING

The specimen was cut in an optimized butterfly geometry for fatigue testing [5] as seen in Figure 2. The specimen is 410 mm long and the cross section is approximately 25 x 5 mm in the gauge area. The tabs, which are in place to protect the material from damage from the grips, are softly tapered towards the gauge region to avoid stress concentrations in the underlying laminate.

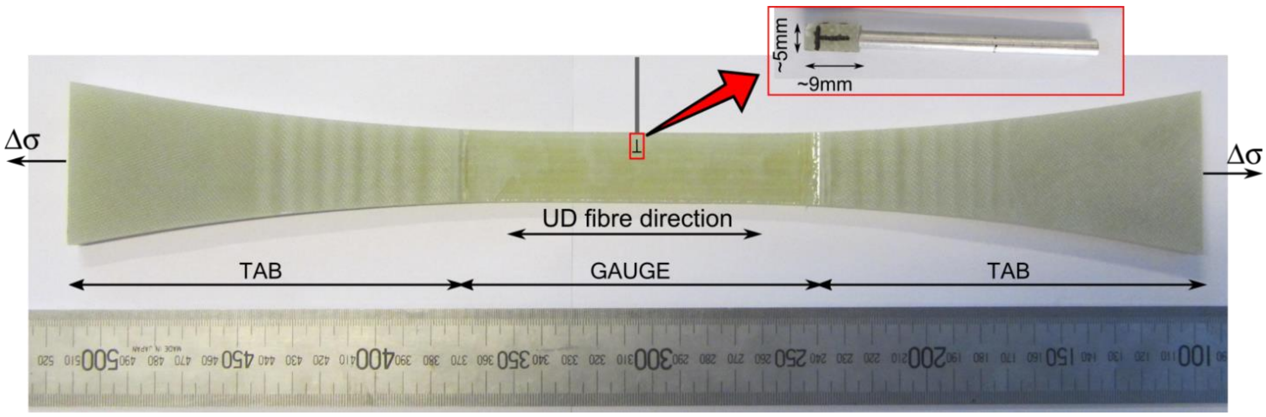


*Figure 2: Indication of approximate position of cut-out in the fatigue test specimen geometry. The specimen geometry is the optimized butterfly geometry (see e.g. [5]]*

Prior to the 3D XCT examination, the specimen was subjected to tension-tension fatigue loading and stopped at around half life time. Half-life time indicates the approximate half-life of the sample deducted from the life-time of several specimens tested to fracture. Figure 3 shows a sketch of the typical stiffness degradation behaviour during tension fatigue for this composite. The half-life is approximately in the centre of the linear part (II) of the stiffness degradation curve

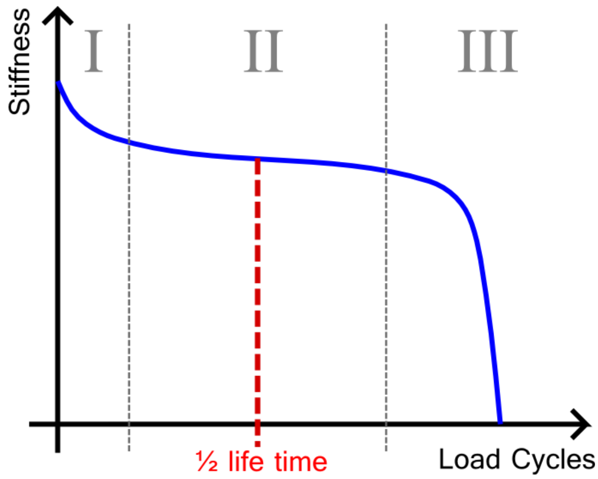


*Figure 3: Typical stiffness degradation curve for composite, with indication of approximate location of half-life time.*

**3D XCT SCAN METHOD**

The experiments were performed on a Zeiss Xradia Versa 520 system, which at optimum conditions can achieve a spatial resolution down to 0.7 microns and a voxel (3D pixel) size down to 70nm. Scans were performed on a ~5x5x9mm cut-out of the fatigue test specimen, which also was indicated in Figure 2. The sample was cut and mounted on an aluminium pin using superglue. Any additional sample preparation is not necessary and the cutting tolerance for this type of scan is not critical for these scans. Four scans were performed on the sample:

1. A large field of view (LFOV) scan, including the whole sample (0.4X detector and voxel size 9.7 microns).
2. A scan at the centre of the sample with higher magnification (4X detector, voxel size 3.37 microns and a field of view on the detector of 3.37x3.37mm.).
3. Similar to scan 2 but 2 mm above the centre of the sample (towards the top).
4. Similar to scan 2 but 4 mm above the centre of the sample (including the top of the sample).

Scan 2-4, which were performed at a higher magnification, are overlapping to make sure that edge effects in the scan do not play a role. In the following presentation of results, scan 2-4 will mainly be treated as one as if the data sets were stitched together. In scan 2-4 it was possible to see individually broken UD fibres with no tension applied, and this will be discussed in the following section.

**RESULTS AND OBSERVATIONS**

Figure 4 shows the 3D reconstructed image of scan 1 on the left-hand side where the matrix material was made invisible using thresholding for easier visualization. It is seen that the entire sample includes 4 whole UD bundles and 8 which have been cut. Additionally the backing bundles are seen on the specimen surface where a variation in orientation angles and several intersections between the bundles are observed. On the right-hand side in Figure 4, an example of a scan performed with the same settings as scan 2-4. The cylindrical shape is a consequence of the way the 3D volume is reconstructed. The approximate dimensions are indicated on this image, and it is seen that the backing layers are thinner than the UD layers. It should be noted that the fibre diameter is around 17 microns; however this material actually also include larger radii fibres of 24 microns at some locations.

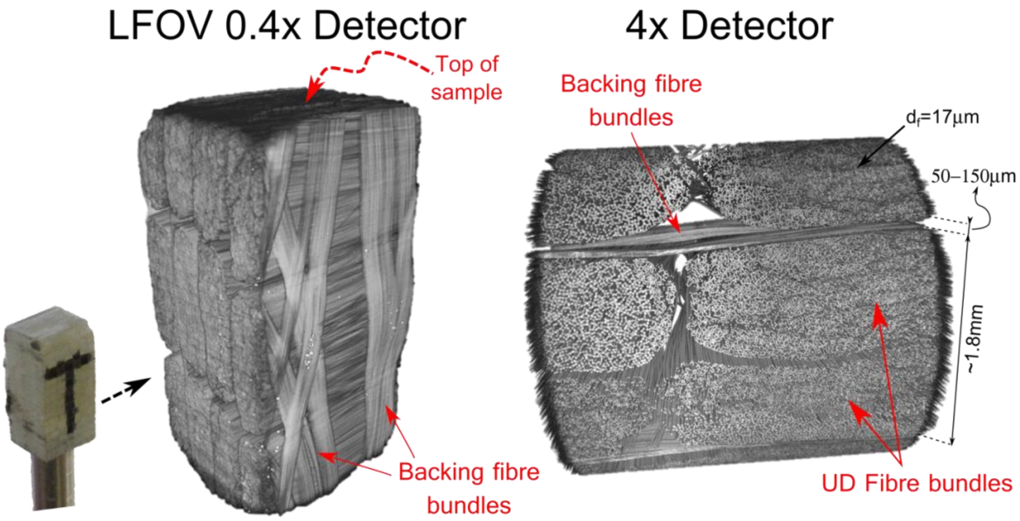


*Figure 4: Examples of 3D reconstructed images for the considered UD glass fibre composite*

***Regions with broken fibres***

Figure 5 shows a 2D view in the centre of the sample obtained by combining scan 2-4. The whole volume, including all three scans, was carefully examined visually. The only locations where broken fibres could be seen are in the three regions of interest (ROI 1-3) indicated in Figure 5. The indicated regions are volumes which continue out of plane in the direction of the UD bundles. Broken fibres were only observed locally close to the backing layers, hence no broken fibres were observed further within the UD bundles or close to the cut surface at the top of the sample. Since no damage was observed at any other positions than locally at the backing, it is not believed that the cutting of the sample has an effect on the marked regions of interests. It should be noted that the observed broken fibres are based on subjective visual inspection.

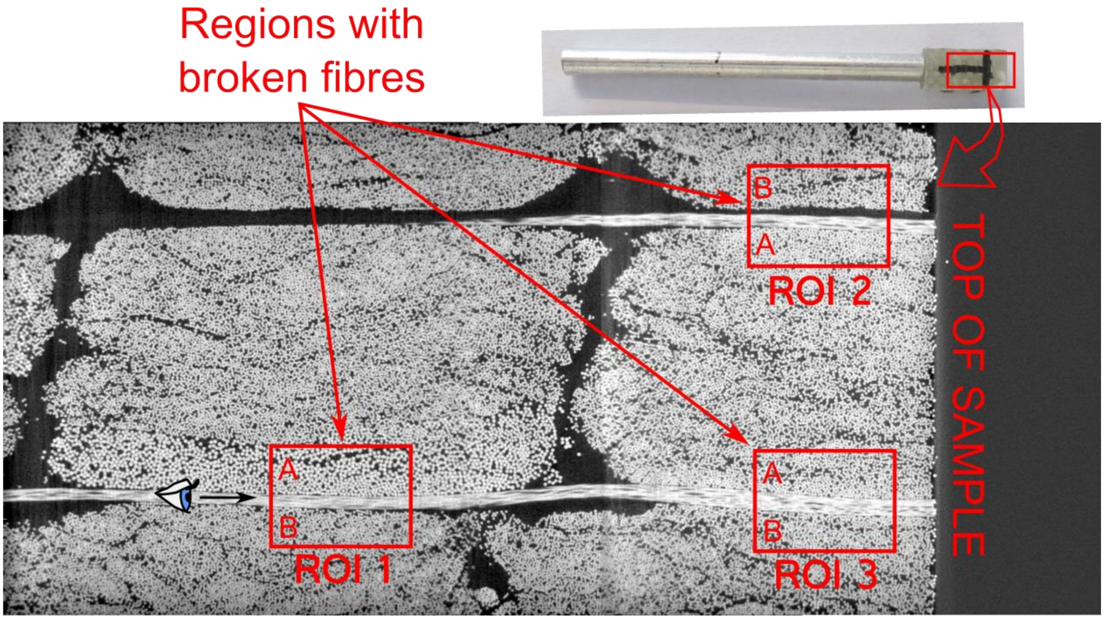


*Figure 5: A 2D slice in the centre of the data set showing regions of interest in relation to broken fibres. Location A marks the side to which the UD bundles are stitched to the backing layer, and B marks the side which is not stitched to the nearby backing layer.*

***Intertwining backing bundles***

Figure 6 shows examples of broken fibres at the three ROIs using the viewing direction indicated in Figure 5.

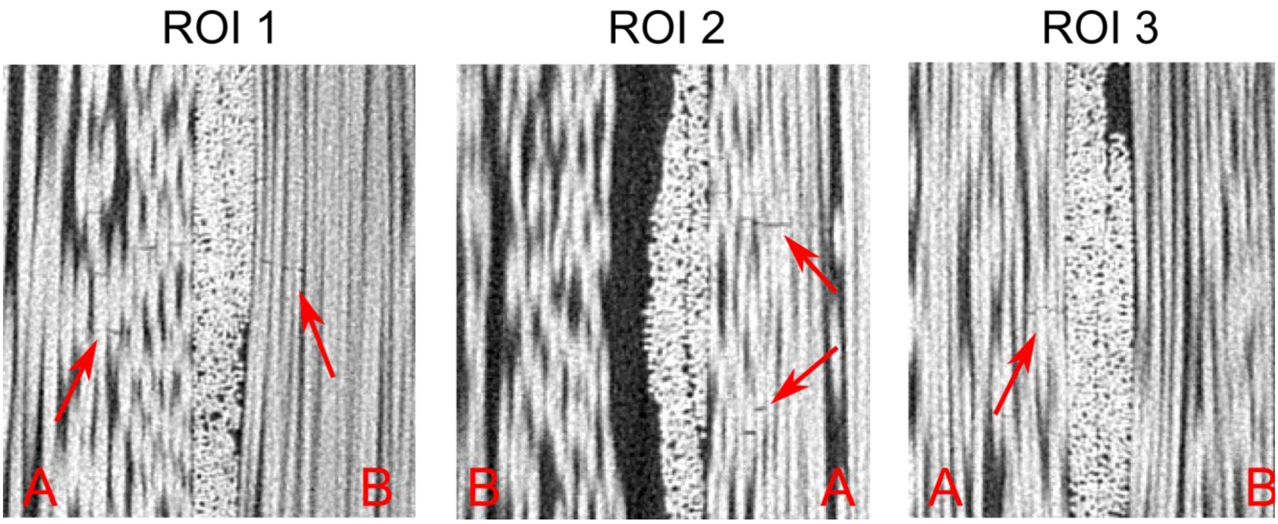


*Figure 6: Regions with observed broken axial fibres all include intertwining backing bundles in direct contact with a UD bundle.*

A common observation for the three locations where broken fibres were observed is the presence of a double backing bundle, which also can be seen in Figure 6. However, broken fibres are not observed at all positions with intertwining bundles in contact with a UD bundle. For this reason it seems that additional factors have an effect on where the fibre fractures occur. It is interesting to note that the axial fibres in side B of ROI 2, Figure

6, are not damaged at all – perhaps due to the resin interlayer. The local fibre misalignment in a plane parallel to the backing layer in the UD bundles in ROI1A is between 5-10 degrees, whereas almost is no misalignment is observed in the other regions with observed broken fibres. Additionally the local fibre volume fraction close to the backing in the ROIs is high, and the fibre diameter is varying. Since there are many factors which can influence the damage progression, further studies on a larger volume should be performed to study the effect in more detail. Performing a quantitative study on a larger volume based on an automated procedure is currently work in progress.

***Distribution of broken fibres***

Figure 7 shows the broken fibre distribution in ROI 1 when looking towards the backing layer at a plane and moving further away from the backing.

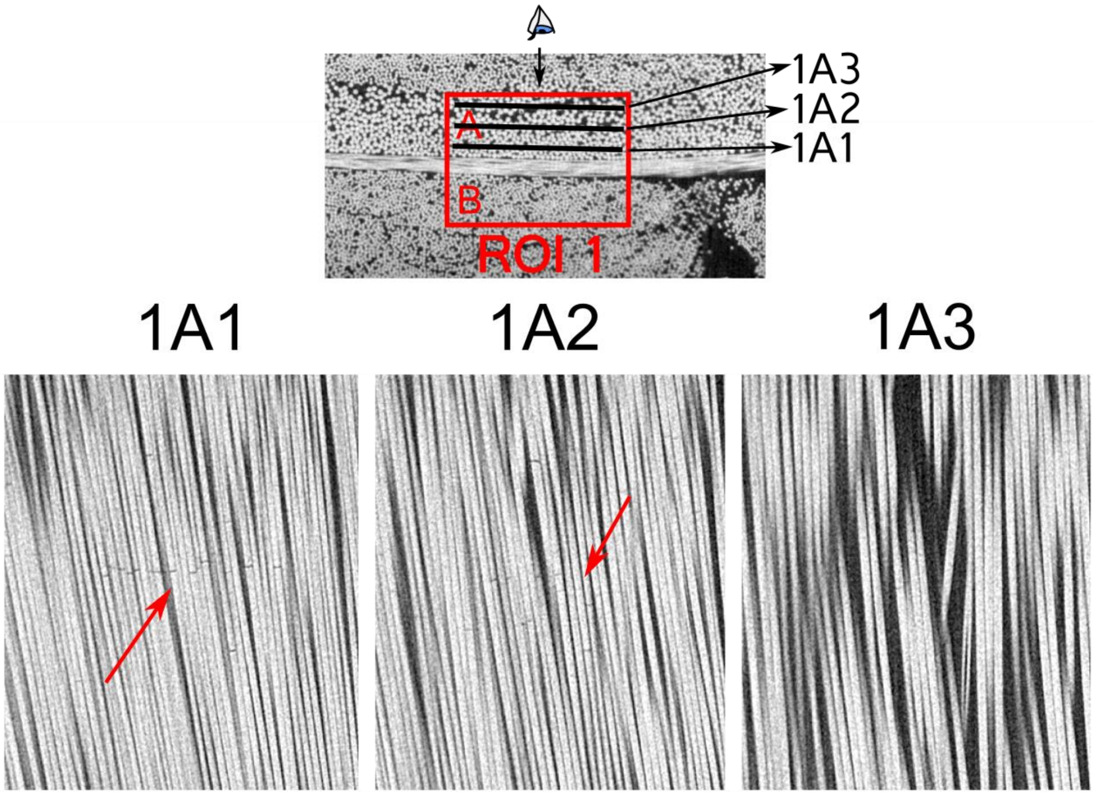


*Figure 7: The distribution of broken fibres in region of interest 1 at three locations.*

Figure 7 the broken fibres are seen to initially be lined up (1A1) in the vicinity of the backing, and spread out in a larger area when moving further into the UD fibre bundle (1A2). It could be that a matrix crack in the backing has propagated into the bundle, causing the almost straight line of breakage, and that these cracks then propagate along the fibre interfaces and penetrate the fibres at weak locations, causing the fibre breaks to spread out. However, it was not possible to see interface or matrix cracks in the performed scans (larger resolution needed), so it cannot be confirmed at this time. The broken axial fibres are only observed locally close to the backing, and it is seen that in ROI1 there are already no observed broken fibres in 1A3, Figure 7. It is likely that this damaged area would keep increasing in size if the fatigue test was continued, as postulated by Zangenberg et al. [4].

## DISCUSSIONS AND CONCLUSIONS

From the results of a set of 3D XCT experiments performed on a fatigue tested UD glass fibre composite material, several observations were done. Broken fibres were observed in the UD bundles locally close to the thin transverse supporting backing layers; however, only at locations with intertwining backing bundles in direct contact with a UD bundle. At locations with broken fibres, a locally high fibre volume fraction is present in the UD bundle. The broken fibres are seen to spread out into an area (damage zone) in the UD bundles locally close to the backing layer. The observations are in good agreement with previous observations by Zangenberg et al. [4] performed using destructive techniques.

It should be noted that, despite examining in 3D, the considered volume is fairly small and therefore only 3 different damage regions are present in the material. Additionally two of the damaged regions are close to the surface of the sample. Therefore it could be useful to perform additional scans to improve the reliability of the observations. However, as there are not observed any broken fibres in the UD bundles at any other locations than the ones marked (even close to the cut sample surface) the cut is not expected to have an effect on the results. In contrast SEM imaging technique are usually looking directly at a cut and grinded surface.

The observations of broken fibres in the current study are based on subjective visual inspection conducted by the author. When using 3D XCT there is a certain level of noise in the image making it difficult to judge whether an observed feature is noise or actually a broken fibre. Since 3D XCT requires a change in material density in order to give contrast in the image, it might not observe broken fibres with a closed crack surface. For this reason, it cannot be said for certain that all broken UD fibres are discovered in this study. A good way of confirming this would be to burn off the resin and examine the fibres in the scanned sample. This will be done in the near future.

## ACKNOWLEGEMENTS

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